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## CHAPTER 2

### OVERVIEW OF THE ASSESSMENT

#### 2.1 SCHEMATIC OF THE ASSESSMENT

Figure 2-1 shows the processes involved in the formation of acid deposition. This report focuses on SO<sub>2</sub> emissions. SO<sub>2</sub> is a gas that is released when fuels containing sulfur, such as coal, are combusted. SO<sub>2</sub> interacts with other elements in the atmosphere to form secondary sulfate aerosols.<sup>1</sup> The resulting sulfate aerosols are called secondary pollutants because they are not emitted directly, but are formed later.<sup>2</sup> The transformation into sulfate aerosols begins within fairly short distances from the source. Sulfate aerosols can be transported long distances through the atmosphere before deposition occurs. Some of them are acidic sulfate aerosols, which are a primary constituent of acid deposition in the eastern United States.

Figure 2-2 shows the relationships among the most common measures of particulate matter in the atmosphere. Different measures are used in different contexts, and many of these terms are used throughout this report. Total suspended particulates (TSP) represent all airborne particulate matter. Particulate matter under 10 microns in aerodynamic diameter (PM<sub>10</sub>) are particles small enough to be inhaled into the airways of the lungs. PM<sub>10</sub> is sometimes called thoracic particulate matter. A smaller size category for particulate matter is fine particles, which are particles with aerodynamic diameter of 2.5 microns or less (PM<sub>2.5</sub>).

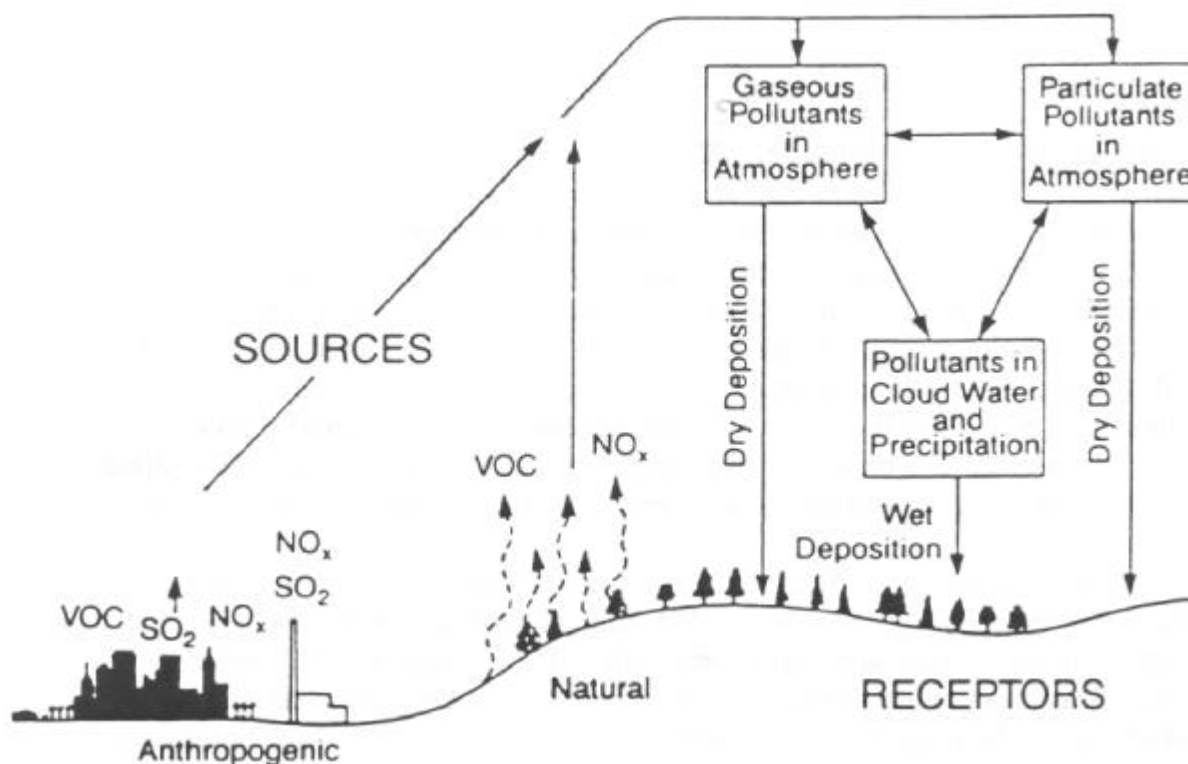
Most sulfate aerosols are part of PM<sub>2.5</sub> and most acid aerosols, in the particle phase, are sulfate aerosols. The term acid aerosol is often used to refer to all airborne acids, including those in the vapor phase such as nitric acid (NAPAP, 1991). Such vapors are outside the definition of any of these particle measures. All acidic sulfate aerosols are particles rather than vapors. Sulfate aerosols make up the largest single component of fine particulate matter in most locations in the eastern United States. Measures of average sulfate aerosol concentrations are about 40 percent of measures of average fine particulate matter levels in the eastern

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<sup>1</sup> An aerosol consists of liquid or solid particles in air.

<sup>2</sup> Some sulfate aerosols are emitted directly from combustion sources. These are called primary sulfate aerosols, but they make up a very small percentage of total ambient sulfate aerosols.

**Figure 2-1**  
**Process Involved in Acid Deposition**



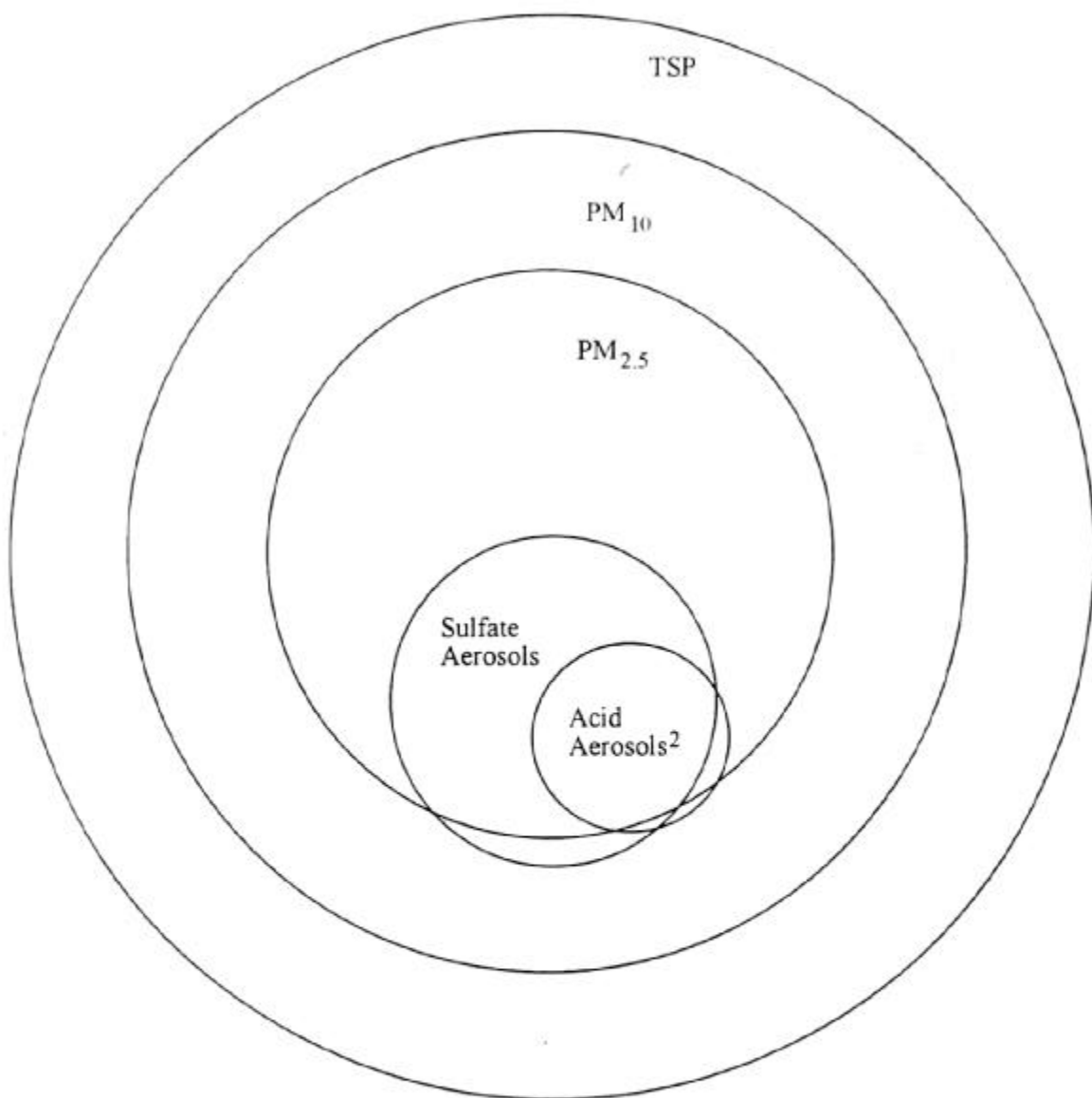
Source: National Acid Precipitation Assessment Program (NAPAP), 1991, p. 174.

United States (Dockery et al., 1993)<sup>3</sup>. Sulfate concentrations are lower in most of the western United States, where fuels with lower sulfur content are more commonly used.

Figure 2-3 shows an overview of the major pathways by which SO<sub>2</sub> emissions may cause human health effects. A comprehensive quantitative assessment of the human health benefits of Title IV must analyze each of these pathways. The Title IV requirements will result in reductions in SO<sub>2</sub> emissions, relative to what would have been emitted in the absence of Title IV. Changes in SO<sub>2</sub> emissions result in changes in human exposures to potentially harmful substances in the ambient air, both near and far from the SO<sub>2</sub> source, and through the effects of acid deposition on mobilization of toxic substances in soils and water.

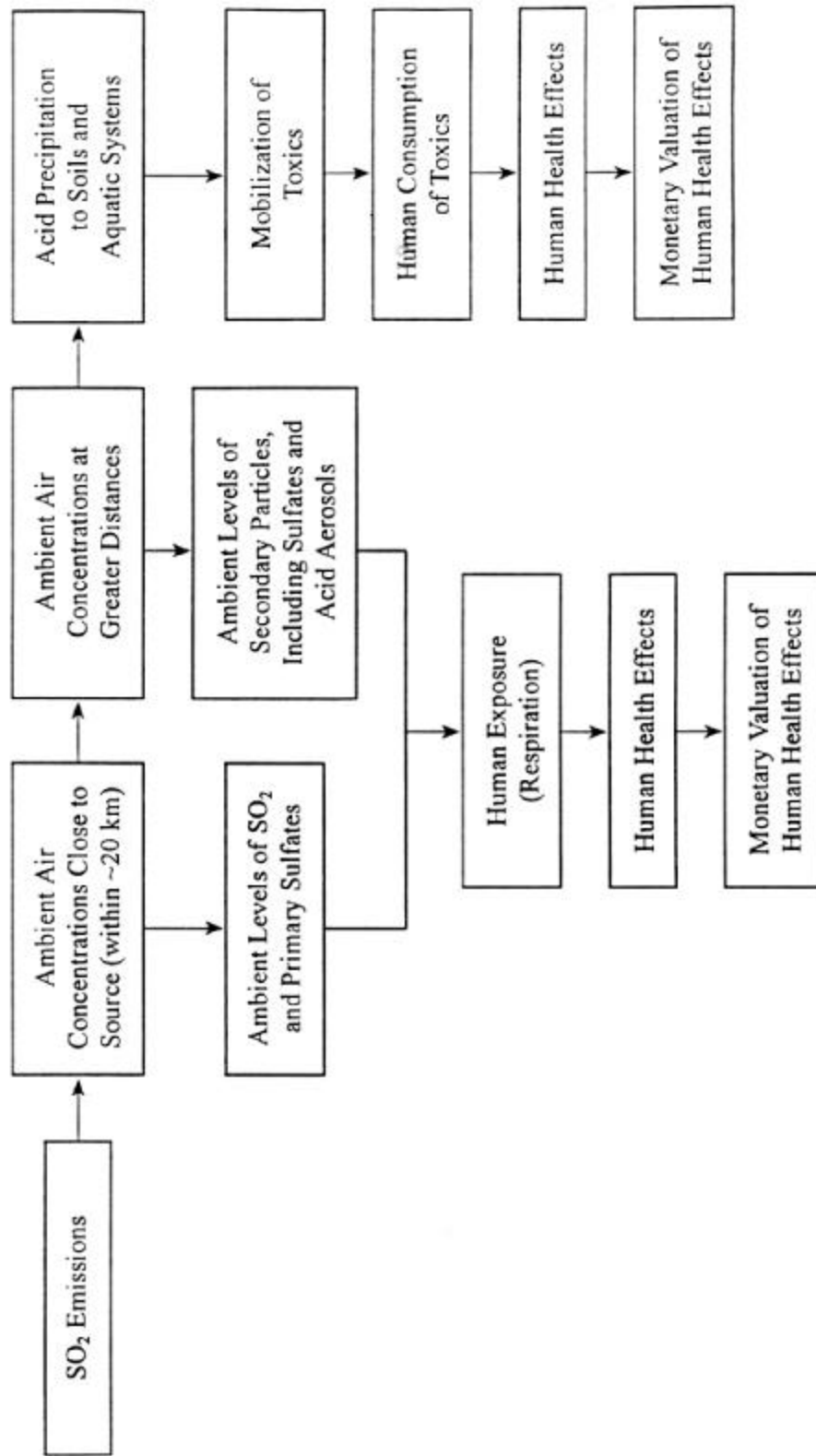
<sup>3</sup> The 1995 review draft of the PM Criteria Document (US EPA, 1995) reports an average ratio of 0.47 in the eastern U.S. and 0.37 in the central U.S. Our definition of "eastern" includes 31 states, some of which fall in what is commonly called "central" U.S. The 0.4 estimate is therefore reasonably consistent.

**Figure 2-2**  
**Alternative Measures of Particulate Matter in Atmosphere**



- <sup>1</sup> This figure shows the overlaps in the different measures, but is not drawn to scale in terms of typical relative proportions in the atmosphere. Such proportions vary from place to place and time to time.
- <sup>2</sup> The term acid aerosols has been used to refer to acids present in the atmosphere in the vapor phase such as nitric acid (NAPAP 1991). Such vapors fall outside the definition of any of these particulate measures. In rare circumstances, such as in the formation of acid fogs, acid aerosols can become larger than  $PM_{10}$  (NAPAP 1991).

**Figure 2-3**  
**Overview of Human Health Effects Resulting from SO<sub>2</sub> Emissions**



November 10, 1995

An important point illustrated in Figure 2-3 is that when SO<sub>2</sub> emissions are reduced, potential benefits to human health occur along several avenues. Reductions in ambient air levels of gaseous SO<sub>2</sub> and sulfate aerosols mean reductions in these potentially harmful pollutants in the air that people breathe. Once the sulfate aerosols are deposited on soils and aquatic systems, the acidic portion of these aerosols can contribute to the mobilization of toxic substances already present in the environment. A reduction in acid deposition thus means a reduction in the chance that these substances will be present in the water and food that humans consume.

For reasons discussed in subsequent sections of this chapter, this report focuses on the human health benefits of the expected reductions in exposure to atmospheric sulfate aerosols caused by the Title IV required SO<sub>2</sub> emissions reductions. Table 2-1 lists the five quantification steps in this assessment and gives a brief explanation of the quantification method selected for each step. Some of the rationale for selecting these methods is explained in subsequent sections of this chapter. Subsequent chapters explain the selected quantification methods in detail.

**Table 2-1**  
**Quantification Steps for this Assessment of**  
**Health Benefits due to Sulfate Aerosol Reductions**

Quantification Steps	Selected Quantification Method
1. Changes in SO <sub>2</sub> emissions in the United States	Use ICF Resources (1994) estimates of 1985 emissions, 1997 emissions with Title IV, and 2010 emissions with and without Title IV (prepared for EPA)
2. Changes in atmospheric sulfate aerosol concentrations in the eastern United States	Use EPA's Regional Acid Deposition Model (RADM) runs for each of the SO <sub>2</sub> emissions scenarios
3. Numbers of people residing at each location where atmospheric sulfate concentrations change in the eastern United States and Canada	Match the RADM 80 km x 80 km grid to population data using a Geographic Information System; population based on 1990 Census data for block groups (Chapter 3)
4. Changes in sulfate-related health effects: changes in numbers of cases of each type of health effect	Use concentration-response functions derived from selected epidemiology studies on health effects of sulfates or PM <sub>2.5</sub> (Chapter 4)

Other related assessments are ongoing at the U.S. EPA, such as the Section 812 studies concerning the costs and benefits of the Clean Air Act Amendments as a whole and the review of the National Ambient Air Quality Standards (NAAQS) for particulate matter. Although there are many similarities in the general approaches being taken in the health benefits components of these other assessments and in this assessment for Title IV, many of the details of the assessment methods may differ. Many of these differences stem from the fact that this assessment focuses on SO<sub>2</sub> emissions and sulfate aerosols only, while the NAAQS assessment considers all sources of ambient particulate matter and the Section 812 studies consider not only all sources of ambient particulate matter but all air pollutants regulated under the Clean Air Act.

The results of this health benefit assessment based on the selected default assumptions are reported in two ways. First, they are reported as annual estimates for the years 1997 and 2010. Title IV, Phase I, is expected to be implemented by 1997, and Title IV is expected to be fully implemented by 2010. The estimated 1997 sulfate concentrations without Title IV are based on Regional Acid Deposition Model (RADM) runs for 1985 emissions estimates, assuming no significant change from 1985 to 1997 in the absence of Title IV. RADM results for 1997 estimated SO<sub>2</sub> emissions with Title IV are compared to 1985 RADM results to calculate Title IV health benefits in 1997. The 2010 estimates are based on ICF Resources estimates of SO<sub>2</sub> emissions with and without Title IV for 2010 and on estimates of ambient sulfate aerosol concentrations from RADM for each of the 2010 emissions scenarios. The annual estimates are based on 1990 population and income levels and are reported in 1994 dollars.

Second, the results are reported as 1995 present value estimates of the total health benefits expected from 1997 through 2010. Health benefits due to Title IV for the years between 1997 and 2010 are interpolated from the RADM-based estimates in proportion to the emissions estimates available for the years between 1997 and 2010 for the scenarios with and without Title IV. Aggregate estimates of total health benefits are reported undiscounted and discounted with two alternative discount rates, both adjusted for average expected population and real income growth.

## **2.2 UNCERTAINTY AND SENSITIVITY ANALYSES**

Any quantitative assessment of this nature is subject to considerable uncertainty due to the complexities of the physical and economic processes involved, and limits in our technical capabilities to fully characterize current interactions and predict future changes. It is important that analysts attempt to characterize the uncertainty in the results of such an assessment so that policy makers can give appropriate consideration to the results in their decision making processes. This report addresses uncertainty in the following ways:

- Limitations and assumptions in the quantification process are clearly stated and explained.

- A quantitative uncertainty analysis is conducted based on estimated statistical variance in some of the underlying relationships upon which the assessment is based.
- Sensitivity analyses illustrate the effects of changing key default assumptions on the mean results of the assessment.

There are many different valid ways to characterize and present quantitative uncertainty in an assessment of this type. This assessment has used an approach very similar to that developed by Rowe et al. (in press) in a quantitative model to estimate environmental effects of electricity generation in New York. The quantitative uncertainty analysis is based on variations in results within and across selected studies, but specific results are selected as most likely correct and are given probability weights that reflect some analyst judgment as well as empirical evidence.

### **2.2.1 Quantitative Uncertainty Analysis**

The available epidemiology and economics evidence regarding health effects associated with air pollutants is subject to considerable uncertainty. Within a given study there is statistically measurable uncertainty in the estimated concentration-response coefficients or monetary value estimates, and there are differences in results obtained from different studies looking at the same or similar health effects. This assessment uses a quantitative uncertainty analysis similar to the approach developed by Rowe et al. (in press). For each concentration-response relationship and each monetary value estimate presented in this report, low, central, and high estimates are selected. The central estimate is typically selected from the middle of the range reported in the study, or group of studies, that has been selected as providing the most reliable results for that health effect based on the study selection criteria.

These ranges of estimates are not intended to reflect absolute upper and lower bounds, but rather they are ranges of estimates that are reasonably likely to be correct, given available epidemiology and economics study results. For example, ranges based on a single study are selected as plus and minus one standard error, not the absolute highest or lowest results obtained. When several different “reliable” studies are available for a given health effect, the selected range reflects the variation in results across the studies. The reader should be aware that there is analyst judgment in selecting these ranges and that the ranges do not reflect all the uncertainty in the estimates because some of the uncertainty is not quantifiable. This is, however, an attempt to give a more realistic presentation than is given when only point estimates are reported.

Each low, central, and high estimate is also assigned a probability weight (the weights summing to 100 percent for each quantified health effect and for each monetary value estimate). These probability weights, combined with the low, central, and high estimates, are used to estimate a probability distribution of the total health benefits estimate, which is calculated by multiplying estimated numbers of health effects by the monetary value per case, and summing across all the

health effects categories. Calculating a probability distribution for the total health benefit estimate provides an alternative to simply summing all the low estimates or all the high estimates to obtain total low and high estimates. Such simple summing results in a misleadingly large range of values, because it is highly unlikely that all the low estimates (or all the high estimates) are correct. When the low, central, and high estimates are based on results from different studies all judged as equally reliable, an equal probability weight is given to the low, central, and high estimates. When only one study result is selected, the range selected is often plus and minus one statistical standard error of the selected central result. When a standard error is used, the probability weight given to the central estimate is 50 percent, with 25 percent each to the high and low estimates. In a few cases less weight has been given to a high or low estimate based on analyst judgment that there is reason to suspect that particular estimate is less likely to be correct than the other available estimates.

Mean, low, and high values for changes in cases of each health effect and for their monetary values were calculated for the estimated change in sulfate concentrations, using the low, central, and high values and the probability weights assigned to each. These calculation were executed using the @RISK supplemental program for such applications with the Lotus 1-2-3 spreadsheet program (Palisade Corp., 1994). This program selects a sample of all the possible combinations of low, central, and high estimates sufficient to estimate a probability distribution for the total health benefit estimate. From this estimated distribution, we have selected low and high values that represent the 20<sup>th</sup> percentile and the 80<sup>th</sup> percentile on the probability distribution of the total estimated health benefit. This means, for example, that there is an 60 percent probability that the “true” value falls between these low and high results, given the magnitudes and the probabilities selected for each of the low, central, and high concentration-response and monetary value estimates.

### **2.2.2 Sensitivities to Key Default Assumptions**

Throughout the report the assumptions and uncertainties in this analysis are acknowledged. In some cases it is possible to define alternative assumptions and to determine how the results are affected if a default assumption were determined to be incorrect. This is an important process for identifying the most important assumptions with regard to their effect on the bottom line, and the results are reflected in the conclusions of the report.



## 2.3 RESULTS FROM THE 1990 NAPAP ASSESSMENT

Three categories of potential human health effects associated with SO<sub>2</sub> emissions and subsequent secondary pollutants were considered in the 1990 NAPAP State of the Science and Technology reports and the NAPAP 1990 Integrated Assessment:

- direct health effects of gaseous SO<sub>2</sub>
- indirect health effects of toxic chemicals released into the environment as a result of acid deposition
- direct health effects of acid aerosols in the ambient air.

### 2.3.1 NAPAP Conclusions on the Effects of Gaseous SO<sub>2</sub>

SO<sub>2</sub> is a criteria air pollutant under the Clean Air Act, and National Ambient Air Quality Standards (NAAQS) have been set to protect public health and welfare. The current primary NAAQS for SO<sub>2</sub> are:

- annual average of 0.03 ppm
- 24-hour average of 0.14 ppm.

Ambient concentrations of SO<sub>2</sub> have been substantially reduced in the United States since 1970, and most of the population now lives in areas that meet the primary NAAQS. Remaining nonattainment areas are limited to geographical areas in the immediate vicinity of a few major point sources.

Much of the recent SO<sub>2</sub> health effects research has focused on acute exposures of asthmatics, who are believed to be more sensitive to SO<sub>2</sub> than other people. Aggravation of asthma symptoms in some individuals who are exercising and who already have asthma has been demonstrated in clinical studies with short-term SO<sub>2</sub> exposures at concentrations close to those that occasionally occur currently in some locations in the United States. Graham et al. (1990) cite conclusions reached by the U.S. EPA that at current SO<sub>2</sub> emission levels in the United States, the only health effect of any concern due to short-term peaks of ambient SO<sub>2</sub> concentrations is the aggravation of asthma symptoms in exercising asthmatics.

NAPAP (1991) reported the U.S. EPA's conclusions that SO<sub>2</sub> concentrations high enough to cause well-documented short-term effects on individuals with asthma currently occur only within about 12 km of a few major point sources in the United States. Graham et al. (1990) report that approximately 100,000 exercising asthmatics may be exposed once each year to SO<sub>2</sub> concentrations high enough and for long enough to cause a reaction in some asthmatics (0.5 ppm

for 5 minutes was the assumption used). Graham et al. cite clinical evidence that approximately 25 percent of asthmatic subjects may have a doubling of airways resistance while exercising when exposed to 0.5 ppm of SO<sub>2</sub>. Not all reactive asthmatics will have symptoms severe enough to be noticeable to them. More recent evaluations (U.S. EPA, 1994) indicate that only about 10 to 20 percent of mild or moderate asthmatics are likely to exhibit lung function decrements in response to SO<sub>2</sub> exposures of 0.2 to 0.5 ppm during moderate exercise that would be of distinctly larger magnitude than typical daily variations in lung function or average changes in lung function experienced in response to other often encountered stimuli (e.g., cold/dry air, moderate exercise, etc.). A more substantial percentage (20 to 25 percent) of such asthmatics exposed to 0.6 to 1.0 ppm of SO<sub>2</sub> experience respiratory function decrements and severity of respiratory symptoms that exceed typical daily variations or response to other commonly encountered stimuli that produce short-lived bronchoconstrictor effects like SO<sub>2</sub>.

A further reduction in SO<sub>2</sub> emissions, beyond current levels, due to Title IV means that this health effect can be expected to be reduced. Because of the limited geographic scope of this effect however, the economic benefit of reducing this effect is relatively small. If we assume an average monetary value of \$34 (see Chapter 5) for preventing a day with aggravated asthma symptoms, the annual aggregate value of preventing this effect would be no more than \$1,000,000 even if all 25,000 affected asthmatics have noticeable symptoms and if the Title IV emission reduction eliminates all of this negative health effect.

The analysis and conclusions reported by NAPAP appear to be sufficient for estimating an upper bound on the likely benefits of Title IV due to reductions in short-term effects of peak SO<sub>2</sub> exposures on exercising asthmatics. This category of health benefits for Title IV appears to be relatively small and is fairly well established. It does not appear to warrant further quantitative analysis at this time.

### **2.3.2 NAPAP Conclusions Regarding Indirect Health Effects of Acid Deposition**

NAPAP (1991) provides a summary of the analysis and conclusions reported by Grant et al. (1990) of potential indirect human health effects due to acid deposition. The pathway for such potential effects is illustrated on the right-hand side of Figure 2-2. The mechanism is that acid deposition can cause potentially harmful substances already present in soils or aquatic systems to be mobilized. These substances may then ultimately be consumed by humans through food or water. Such consumption in sufficient quantity may cause adverse health effects.

Grant et al. (1990) assessed the likelihood that current levels of acid deposition could be associated with significant human health effects as a result of the mobilization of methylmercury, lead, cadmium, arsenic, aluminum, copper, selenium, and asbestos. This assessment was made difficult by complexities and uncertainties about the physical processes, the multiple sources of

these substances in the environment, and human exposures. The conclusions are therefore tentative, but they appear to be reasonable given currently available information.

Grant et al. (1990) concluded that at current acid deposition levels, lead and methylmercury are the only substances considered that may be causing measurable health effects as a result of acid deposition. Some subpopulations of individuals are already exposed to high levels of these compounds because of circumstances unrelated to acid deposition, and it is feasible that further exposure due to the mobilization effects of acid deposition might result in adverse health effects. For lead, critical health effects include slowed fetal physical and neurological development, neurobehavioral deficits in young children, including decreased IQ, and hypertension in adults. Critical health effects due to methylmercury include fetal psychomotor retardation and paresthesia in adults.

Only a small segment of the population is likely to be at any appreciable risk because of incremental lead or methylmercury exposures as a result of current levels of acid deposition. The population segments judged to be at some potential risk are as follows:

- ▶ Those for whom subsistence fishing is a significant source of food and who fish primarily at acidified lakes may be at risk of harmful effects due to methylmercury in fish. High concentrations of methylmercury have been measured in fish at acidified lakes in the upper Midwest and Northeast.
- ▶ Young children and developing fetuses within pregnant women who consume acidified drinking water (without pH or corrosivity treatment) may be exposed to potentially harmful concentrations of lead if the soil or water distribution system contains lead that is leached by the acidified drinking water. These are primarily individuals whose drinking water comes not from municipal systems but from rainwater, surface water, or shallow wells.

Grant et al. (1990) estimate that the first group may contain as many as 10,000 individuals and that the second group may contain approximately 11,000 children and 29,000 women of childbearing age. Estimates of how many of these individuals might be expected to suffer adverse effects were not made, but clearly it would be some fraction of the total. Although some potential health effects of these substances are severe, the number of people estimated to be at any risk of elevated exposure at current acid deposition levels is small.

Uncertainty about the current extent of these health risks due to acid deposition cannot be reasonably reduced at this time without an investment of very significant research resources. Further quantitative analysis of this category of potential health effects does not appear to be warranted at this time.

### 2.3.3 NAPAP Conclusions on the Effects of Acid Aerosols

Graham et al. (1990) reviewed the available laboratory, clinical, and epidemiological evidence on the human health effects of acid aerosols. NAPAP (1991) summarized the conclusions of this review, which are that (1) there is evidence of harmful respiratory effects for human subjects exposed to some types of acid aerosols and (2) there is not sufficient information available to conduct a quantitative assessment of the current level of health effects due to acid aerosols in the United States.

Acid aerosols are a mixture of several pollutants. In the eastern United States, the predominant fraction of acid aerosols appears to be acidic sulfates, which include sulfuric acid ( $\text{H}_2\text{SO}_4$ ), ammonium bisulfate ( $\text{NH}_4\text{HSO}_4$ ), and ammonium sulfate [ $(\text{NH}_4)_2\text{HSO}_4$ ]. NAPAP (1991) notes that the hydrogen ion ( $\text{H}^+$ ) may be the species of concern with respect to human health, but this remains uncertain. Most of the available laboratory and clinical evidence regarding health effects of acid aerosols focuses on acidic sulfates, especially  $\text{H}_2\text{SO}_4$ . NAPAP summarizes the available clinical and laboratory evidence on acidic sulfates as follows:

- ▶ Controlled acute exposures to acidic sulfates can cause decreased lung function and reactivity responses in some asthmatics.
- ▶ Controlled acute exposures to acidic sulfates can alter mucociliary clearance of the lungs in nonasthmatic and asthmatic humans. This may affect the ability of the lungs to clear inhaled particles, including infectious organisms.
- ▶ Long-term exposures of laboratory animals to acidic sulfates reveal changes related to the development of chronic bronchitis, including reduced mucociliary clearance and morphological changes.

Epidemiology research concerning acid aerosols has been quite limited because of little availability of data on ambient acid aerosol concentrations. NAPAP (1991) notes that there is epidemiology evidence that air pollution mixtures known to contain acid aerosols are associated with both mortality and morbidity, but that it is not possible to determine to what extent this association is due to the presence of acid aerosols. Four aerosol pollution measures that have been used in these types of studies are TSP,  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ , and sulfates. NAPAP notes that statistically significant associations between mortality and all of these aerosol measures have been found in macroepidemiological studies, and somewhat more consistency has been found in the results for fine particles and sulfates. The macroepidemiological studies compare average mortality rates across locations with different average pollution concentrations.

The NAPAP 1990 Integrated Assessment appropriately concluded that there is not sufficient information available at this time to conduct a credible quantitative assessment of the health effects of acid aerosols in the United States. This is the result of limited data availability for

current concentrations of acid aerosols, as well as limited quantitative evidence on the specific health effects that might be expected for a given concentration of acid aerosol exposure.

The NAPAP assessment, however, did not address the question of whether a quantitative assessment is feasible for sulfate aerosols in general, rather than for just acidic sulfates. This is really the more relevant question with regard to the health benefits of Title IV, because the required reductions in SO<sub>2</sub> emissions will result in reductions in all sulfate aerosols, not just acidic sulfates.

## **2.4 FOCUS OF THIS ANALYSIS ON SULFATE AEROSOLS**

The focus of this analysis is on the potential human health benefits of the reduction in ambient concentrations of sulfate aerosols, including acidic sulfates, that is expected as a result of the Title IV required reductions in SO<sub>2</sub> emissions. This is the middle path in Figure 2-3. This focus was chosen for four primary reasons:

- ▶ A quantitative assessment of the health benefits of reducing ambient sulfate aerosol concentrations is feasible given available information, but has not yet been conducted for the type of change in ambient concentrations expected as a result of Title IV.
- ▶ A large available body of epidemiology literature concerning the association between ambient aerosol pollutants, including sulfates, and human health effects allows a quantitative assessment to be performed using a modest amount of research resources.
- ▶ The required reduction in SO<sub>2</sub> emissions is substantial relative to current emission levels, and the resulting reduction in ambient sulfate aerosol concentrations is also expected to be substantial.
- ▶ Given the potential for reductions in risks of mortality, chronic respiratory disease, and acute morbidity as a result of reductions in sulfate aerosol concentrations, and the long distance and wide ranging dispersion of sulfate aerosols, there is a possibility of substantial health benefits.

The other two branches of Figure 2-3, direct effects of gaseous SO<sub>2</sub> and indirect effects of acid deposition, were examined in detail in the 1990 NAPAP analyses. The results suggest that the number of people at potential risk of health effects due to these pathways under current conditions is fairly limited. The potential that these risks will be reduced as a result of Title IV should not be disregarded in a comprehensive assessment of Title IV benefits, but it does not appear that there are sufficiently different data or analysis approaches available today to warrant further analysis of these potential health effects pathways at this time.

## 2.5 GENERAL LIMITATIONS OF THE ASSESSMENT

Detailed discussions of the assessment approach, assumptions, and limitations are provided in Chapters 3, 4, and 5. In this section, we introduce and highlight what we believe are the key difficulties, limitations, and uncertainties in this assessment and therefore in the results.

This health benefits assessment relies on results of two other analyses conducted for or by EPA. These are the ICF Resources (1994) estimates of emissions of SO<sub>2</sub> with and without Title IV, and the EPA estimates of resulting ambient sulfate aerosol concentrations using RADM with the ICF emissions estimates as input. Each of these analyses relies on specific applications of detailed models developed for these and other purposes, which are briefly described in Chapter 3. Detailed discussions of these analyses, key assumptions, and uncertainties and limitations are provided elsewhere (e.g., ICF Resources, 1994; Chang et al., 1990; Dennis et al., 1990; Dennis et al., 1993), and are not the focus of this report. This report focuses on the approach used to quantify and value health effects associated with these previously estimated changes in ambient sulfate aerosol concentrations, and we provide a thorough discussion of the strengths and limitations of the health effects quantification and valuation procedures. We do not provide a detailed assessment of the analyses conducted previously that we rely upon in this report, but it is important to acknowledge that there is uncertainty in each of these analyses and results, which adds additional uncertainty to the final results of this analysis.

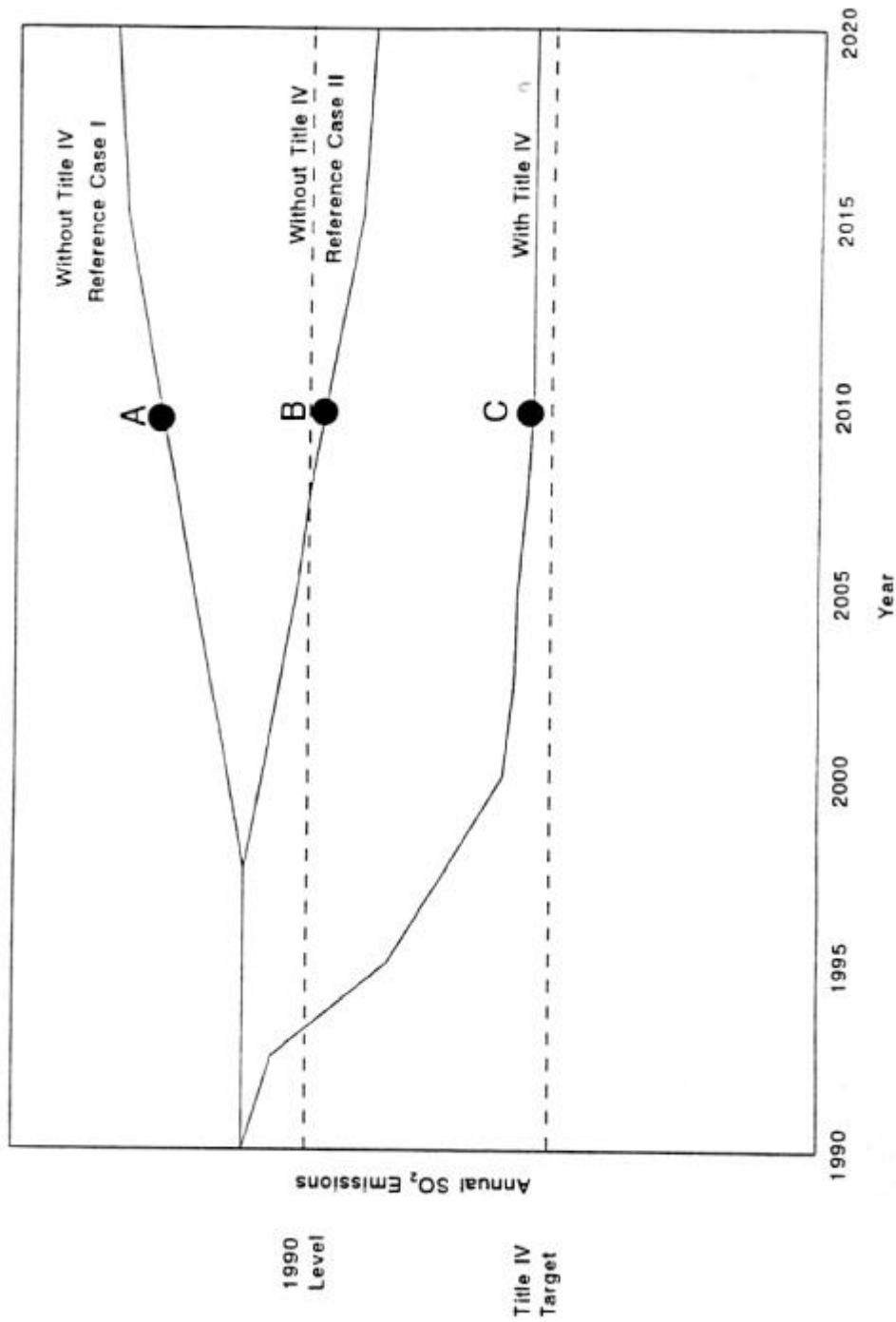
### 2.5.1 Key Uncertainties in Step 1: Estimating Changes in SO<sub>2</sub> Emissions

To estimate the benefits of Title IV it is necessary to make some assessment of what would have happened in the absence of the Title IV requirements. The benefits of Title IV are then calculated based on the difference between SO<sub>2</sub> emissions levels with and without the Title IV requirements for each future year included in the analysis. Possibly the greatest uncertainty in the first step in the analysis is in estimating what SO<sub>2</sub> emissions would have been over time in the absence of the Title IV requirements.

We refer to the estimate of what emissions would have been without the Title IV requirements as the reference case emissions estimates. For this analysis, we use SO<sub>2</sub> emissions estimates developed by ICF Resources (1994) for the EPA's Acid Rain Division for with Title IV and without Title IV scenarios. These estimates go through the year 2010. The reference case emissions estimates show a slight increase in total annual emissions between 1995 and 2005, and are fairly flat after 2005.

Figure 2-4 illustrates the potential significance of this reference case estimate for the calculation of Title IV benefits. The intent of this figure is to illustrate the potential importance of this question. It is not drawn to scale based on actual quantitative estimates. With Title IV, we expect SO<sub>2</sub> emissions will decline sharply in 1995 and come close to the Title IV target by the year 2000.

**Figure 2-4**  
**Illustration of Potential Changes in SO<sub>2</sub> Emissions**



<sup>1</sup> This figure illustrates the potential effect of uncertainty in the reference case emissions estimate. Reference Cases I and II are hypothetical estimates and are not drawn to scale based on any actual estimates.

Potential use of banked emissions allowances will probably mean that the Title IV target will not be entirely met until 2010. Point C represents expected emissions in 2010 with Title IV. Without Title IV, SO<sub>2</sub> emissions might be higher, lower, or at the same level as in 1990. Reference Case I illustrates that if without Title IV emissions would have risen slightly by 2010, then the emissions reduction attributable to Title IV would be the difference between point A and point C. If, on the other hand, emissions would have decreased slightly in the absence of the Title IV requirements, as shown in Reference Case II, the emissions reduction attributable to Title IV would be the difference between point B and point C. Thus, the predicted reference case of what emissions would have been in the absence of Title IV can make a big difference when it comes to estimating the benefits of Title IV.

Even without the Title IV requirements, there are many regulatory and economic factors that are expected to affect SO<sub>2</sub> emissions over the next several decades. NAPAP (1991) reports that future trends in SO<sub>2</sub> emissions without Title IV, would be expected to eventually result in emissions as low as are required under Title IV, but it is highly uncertain how fast this reduction would have occurred. This eventual reduction in emissions, in the absence of Title IV, would be expected to occur because of replacement of old facilities with new facilities that must conform to the stricter New Source Performance Standards under previously established requirements of the Clean Air Act and that have new cleaner technologies available that are more cost-effective to install with new facilities than to retrofit into old facilities.

### **2.5.2 Key Uncertainties in Step 2: Estimating Changes in Sulfate Aerosol Concentrations**

Changes in sulfate aerosol concentrations are based on the intermediate results of RADM, a model developed to estimate acid deposition in the eastern United States as a function of SO<sub>2</sub> emission levels in specified locations. The transformation SO<sub>2</sub> emissions into sulfate aerosols, and the transport of SO<sub>2</sub> and sulfate aerosols through the atmosphere, is a function of complex chemical and meteorological interactions. RADM estimates these relationships for a sample of representative meteorological conditions and predicts annual sulfate concentration distributions at each location based on the estimated frequency of the defined alternative meteorological conditions. RADM has been thoroughly evaluated and tested as reported by Chang et al. (1990), Dennis et al. (1990), and Dennis et al. (1993). One of the most significant uncertainties in using the RADM estimates of airborne sulfate concentrations is that average meteorological conditions do not occur every year. This means that for any given year, the predicted concentrations are less reliable than over a multiple year period over which average meteorological conditions are more likely to prevail.



### **2.5.3 Key Uncertainties in Step 3: Matching Population to the Sulfate Changes**

The RADM grid cells are used as receptor locations to estimate the change in sulfate concentrations for the population. Residents are matched to RADM grid cells assuming that they are all located at the centroid of their census block group. Census block groups cover fairly small geographic areas, so the uncertainty introduced in this step is minimal. Greater uncertainty may exist as a result of people spending a significant share of their time at locations other than where they live. Close by locations such as travel to work create limited uncertainty because the sulfate gradient is fairly gradual from cell to cell. Considerable error could exist for individuals who spend a significant share of the year in locations far from their primary residences. However, this is not likely to be a significant source of uncertainty in this assessment relative to the other sources of uncertainty that are present.

### **2.5.4 Key Uncertainties in Step 4: Estimating Health Effects**

Relying on available epidemiological evidence for estimating health effects associated with human exposure to ambient sulfate aerosols has many advantages, which are discussed in Chapter 4. The primary advantage is that it makes a quantitative assessment feasible with limited research resources and it uses a great deal of health effects evidence that is readily available. There are, however, several important uncertainties and limitations that result from the limitations of the available epidemiological evidence. The three uncertainties that we believe are the most potentially significant as a result of the limitations of the epidemiology evidence are summarized in this section. These and other uncertainties in the health effects calculations are discussed in more detail in Chapter 4.

First, there is uncertainty about the specific biological mechanisms that underlie the observed relationships in epidemiological studies, which raises uncertainty about the confidence with which the results should be interpreted as causative. Epidemiology studies are able to demonstrate whether a statistically significant relationship exists between health effects and pollution concentrations, but the studies do not prove that the relationship is causal. It is possible that a statistically significant relationship is really due to some unidentified factor that is correlated with pollution concentrations. The causation hypothesis is strengthened when epidemiological results are supported by repeated observation in different studies and by biological plausibility and consistency with evidence from other types of health effects studies. Although there is laboratory and clinical evidence of health effects associated with sulfates, as discussed in Chapter 4, the exact biological mechanisms that underlie the observed epidemiological association have not been established. This adds some additional uncertainty that is difficult to fully delineate when using epidemiological relationships to predict how health may change as a result of changes in ambient sulfate aerosol concentrations.

Second, there is uncertainty about the relative harmfulness of sulfates versus other types of pollutant aerosols that are typically present in the ambient air. Sulfates are a significant share of the mix of fine particulate matter in the ambient air in many locations in the eastern United States. Some epidemiology studies have included sulfate concentrations as a measure of pollution, as well as more comprehensive measures of particulate matter such as  $PM_{2.5}$  or  $PM_{10}$ . In some cases, epidemiology studies have found a statistically stronger association between health effects and sulfates (e.g., Plagiannakos and Parker, 1988), and other studies have found a stronger association with the more comprehensive measures of particulate matter (e.g., Dockery et al., 1992). Because of the typically high correlation among sulfates and other measures of fine particulate matter in the ambient air, it is difficult to statistically isolate the effects of sulfates alone in epidemiology studies. For this analysis, we examine the clinical, laboratory, and epidemiology evidence as a whole to determine reasonable assumptions about the relative contribution of sulfates to the epidemiological evidence of an association between health effects and fine particulate matter, but this remains an important uncertainty in the analysis.

Third, there is uncertainty about the extent to which health effects occur at lower ambient sulfate concentrations. For sulfate aerosols, and for particulate matter in general, it remains uncertain whether there is a threshold concentration below which health effects no longer occur, or whether the slope of the concentration-response function diminishes significantly at lower concentrations. Epidemiological studies do not always consider the question of thresholds, and epidemiological data are not always sufficient for making such a determination. Many recent epidemiology studies show a statistically significant association between sulfate concentrations and health endpoints over ranges of sulfate concentrations that are typical of current conditions in the eastern United States. For the mean estimates in this assessment we adopt the default assumption that there is no threshold for health effects associated with sulfates. Sensitivity analysis is used to show how the results might change if in fact some threshold exists at selected alternative concentrations.

### **2.5.5 Key Uncertainties in Step 5: Estimating Monetary Valuation of Health Effects**

There are many uncertainties in available estimates and interpretations of monetary valuation for changes in human health effects. Although it is quite clear that changes in human health have both financial and nonfinancial significance to human welfare, determining appropriate monetary measures of the total effect on human welfare is a difficult task. The uncertainty in the monetary estimates is probably greatest for premature mortality risks. Sources of uncertainty in all the monetary estimates are discussed in Chapter 5, but here we highlight two key uncertainties in the monetary value estimates for premature mortality risks.

The first source of uncertainty in the monetary estimates for premature mortality is that there is little empirical economic evidence available about how health status or life expectancy affects an individual's willingness to pay for changes in risks of premature death. Available willingness-to-pay estimates for changes in risks of death are drawn primarily from samples of adults of average

age distributions and average health status. It is possible that many of those at greatest risk of premature mortality because of air pollution exposure are elderly or in relatively poor health. The available empirical evidence on this question is discussed in Chapter 5, but considerable uncertainty remains.

The second source of uncertainty in the monetary estimates for premature mortality is that most of the available estimates are for changes in the risks of accidental death rather than death due to illness, which is more the issue for pollution exposure. This is because the economic literature concerning monetary values for changes in risks of death has been able to exploit available data on wage differentials as a function of different levels of on-the-job risks of fatalities. It is uncertain whether individuals might have different reactions to risks due to illness rather than accidents, and how this might affect willingness to pay to avoid or reduce such risks. There is some evidence that risks of death due to particularly feared illnesses, such as cancer, are considered more abhorrent than risks due to accidents, but that evidence is limited.